Modeling Abrupt Change in Global Sea Level due to Ocean–Ice-sheet Interaction

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Introduction

Ice shelves are an important interface between the atmosphere, ocean and cryosphere. Recent episodes of ice-shelf disintegration ([3],[4]) and associated land-ice acceleration have highlighted the influence of ice-shelves on the mass balance of the Greenlandic and West Antarctic ice sheets.

The relative importance of mass loss from ice shelves by iceberg calving and by melting varies significantly between ice shelves. For instance, mass loss from the floating terminal shelf of Petermann Glacier in northern Greenland is observed to be mainly due to sub-shelf melting in [5]. The sub-shelf melting at Petermann Glacier is also strongly channelized along the flow direction, which suggests that a stable circulation under the shelf reinforces the melt pattern. The basic hypothesis of this work is that, in general, the meltwater circulation under an ice shelf feeds back on the spatial melt pattern and that it modulates iceberg calving downstream by changing the structural character of the ice shelf.

Current numerical models ([1], [2]) of meltwater plumes under the Filcher-Ronne Ice Shelf and Pine Island Ice Shelf (PIIS) have emphasized the plume dynamics and spatial variation of melting and refreezing. A specific aim of our work is to account for the regular undulations in ice-shelf thickness that are visible in satelite images of PIIS, especially in the areas with the greatest plume velocities (according to [2]).

If melting is concentrated near the grounding line as reported in [2] then gradual advection of the ice would seem to produce a downstream ice draft that varies monotonically, unless seasonal variation in the thermodynamic properties of the High Salinity Shelf Water modulates the melt rate. We should expect that internal dynamics of the ice would tend to erase any significant variations in draft. Therefore, either the process of thickness advection is too slow to erase the unduluations or else there is a feedback process that reinforces the undulations. We hypothesize that the sub-shelf circulation reinforces the melt-induced draft undulations and we will test this idea with suitable numerical modeling.

Model Equations

Meltwater Plume equations following [1] (with frazil ice dynamics suppressed for simplicity):

Thickness equation:

$$\frac{\partial D}{\partial t} + \nabla \cdot (D\mathbf{u}) = e' + m' + p'$$

Momentum equation in x-direction (similar in y-direction):

$$\frac{\partial (DU)}{\partial t} + \nabla \cdot (D\mathbf{u}U) = \nabla \cdot (A_h D \nabla U) + \frac{gD^2}{2\rho_0}\frac{\partial \rho_m}{\partial x} + g' D \frac{\partial A}{\partial x} - c_d U|\mathbf{u}| + DfV$$

Temperature equation:

$$\frac{\partial T}{\partial t} + \nabla \cdot (D\mathbf{u}T) = \nabla \cdot (K_h D \nabla T) + e'T_a + m'T_b - \gamma_T|\mathbf{u}|(T - T_b) + Q_f$$

Salinity equation:

$$\frac{\partial (DS)}{\partial t} + \nabla \cdot (D\mathbf{u}S) = \nabla \cdot (K_h D \nabla S) + e'S_a$$

Ice-shelf equations following [6] (before asymptotic approximations):

Height equation (incompressibility):

$$\nabla \cdot (u_1, u_2, u_3) = 0 \quad \text{which implies} \quad \frac{\partial H}{\partial t} = -\nabla \cdot \int_B^{B+H} (u_1, u_2)\, dz$$

Force balance in x-direction (similar for y-direction):

$$0 = -\frac{\partial p^*}{\partial x} - \rho_I g \frac{\partial (B+H)}{\partial x} - \sum_i \partial_i \sigma_{xi}$$

Force balance in z-direction:

$$0 = -\frac{\partial p^*}{\partial z} - \sum_i \partial_i \sigma_{zi}$$

Flotation condition:

$$H = (\rho_0/\rho_I)(-B)$$

Constitutive Law (Glen's flow law):

$$\dot{\epsilon}_{ij} = (A\sigma^{n-1})\sigma_{ij}$$

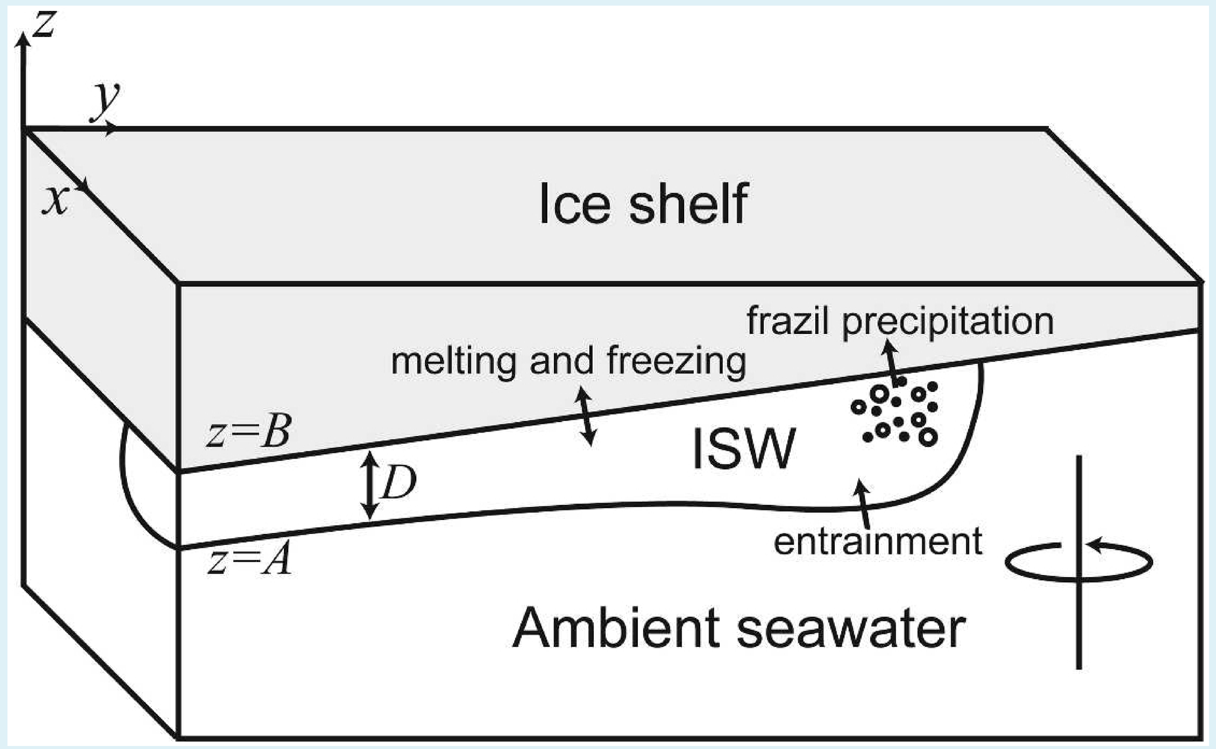
Definition of strain:

$$\dot{\epsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Definition of effective stress:

$$2\sigma^2 = \sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 + 2(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)$$

Ice Shelf and Plume



Definition of coordinates and schematic of relevant processes.

Variables:

$\mathbf{u} = (U, V) =$ depth-integrated velocity

$D = B - A =$ plume thickness

$T =$ depth-averaged temperature

$S =$ depth-averaged salinity

$e' =$ entrainment rate of underlying HSSW

$m' =$ melt rate at the ice-plume boundary

$p' =$ precipitation rate of frazil ice onto ice

$Q_f =$ heating due to frazil ice formation ([1])

$(\rho_0, \rho_I) =$ densities of seawater and ice

$\rho_m =$ density of plume and frazil ice mixture

$H =$ ice shelf thickness

$(u_1, u_2, u_3) =$ ice velocity

$p^* =$ non-lithostatic pressure (diff. btw. isotropic stress and overburden weight)

$\sigma_{ij} =$ deviatoric (traceless) stress tensor

$\dot{\epsilon}_{ij} =$ Cauchy strain tensor

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